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Effects of the uplifts of the main and marginal Tibetan Plateau on the Asian climate under modern and ~30 Ma boundary conditions

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ABSTRACT

The surface uplift of the Tibetan Plateau (TP) had important effects on the evolution of both the regional and global climate during the Cenozoic. Geological evidence indicated that the timing of the uplifts of the main and marginal TP was probably different. However, many previous modelling studies only investigated the effects of the uplift of the whole TP on climate under modern boundary conditions and it remained unclear what was the difference between the effects of the uplifts of the main and marginal TP on climate and how changed boundary conditions influenced these effects. We used numerical modelling to investigate these questions. Our modelling results indicated that the uplifts of the main and marginal TP had different effects on climate. In particular, under modern boundary conditions, the uplift of the main TP decreased annual precipitation throughout inland Asia and in South Asia, increased annual precipitation in East Asia, and markedly changed the summer and winter low-level winds in Asia. By contrast, the uplift of the marginal TP increased the annual precipitation in South Asia, strengthened the seasonality of winds and enlarged the monsoon domain in East Asia. Thus, although the main TP was the major part of the TP in spatial terms, its uplift did not have the dominant effects on climate in all aspects. Moreover, changes in the boundary conditions – for example, from modern to ~30 Ma – could further influence the effects of the uplifts of the whole TP and its sub-regions on climate, particularly for the precipitation in South Asia and monsoon domain in East Asia. These results highlighted the different effects of the uplifts of the main and marginal TP on climate and emphasized the importance of accompanied boundary conditions when investigating the effects of the uplifts of the whole TP and its sub-regions on climate.

1. Introduction

The surface uplift (hereafter abbreviated to the "uplift") of the Tibetan Plateau (TP) was one of the most important tectonic events in the Cenozoic (Zachos et al., 2001). Although there is still debate about the uplift history of the TP (Tapponnier et al., 2001; Harris, 2006; Dupont-Nivet et al., 2008), many researchers agree that different regions of the TP were uplifted asynchronously (e.g., Tapponnier et al., 2001; Wang et al., 2008). Geological evidence suggests that the main TP, including the central and southern TP, had probably already reached an elevation of ~4000–5000 m by the late Eocene (e.g., Tapponnier et al., 2001; Wang et al., 2008; Quade et al., 2011; Searle et al., 2011; Lippert et al., 2014), whereas the marginal TP, including the western TP, the eastern TP, the northern TP and the Tianshan Mountains, probably uplifted later (e.g., Sun et al., 2004; Clark et al., 2005; Fang et al., 2005; Yuan et al., 2013; Li et al., 2014; Li et al., 2015; Yang et al., 2016; Clift et al., 2017). Thus, within the uncertainties of the uplift history of the TP, there is an uplift scenario in which the main TP uplifted first, followed by the uplift of the marginal TP.

Many modelling studies investigated the effects of the uplift of the whole TP on climate (e.g., Kutzbach et al., 1989; An et al., 2001; Liu and Yin, 2002; Abe et al., 2003; Jiang et al., 2008; Botsyun et al., 2016; Li et al., 2016), although some recent modelling studies focused on the effects of the asynchronous uplift of the TP on climate (e.g., Zhang, R. et al., 2012, 2015; Tang et al., 2013). In spatial terms, the main TP is the major part of the TP and the marginal TP is the minor part. However, the effects of the uplifts of the main and marginal TP on climate have not been compared directly. We still do not know whether the uplift of the main TP mainly contributes to the effects of the uplift of the whole TP on climate. If the TP rose early in the Cenozoic, then the

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Table 1
Experimental design.

Experiment	Boundary conditions
Modasia-ntp	Modern geography and SSTs; topography in Asia east of 65° E higher than 300 m set to 300 m; modern land cover; CO_2 = 280 ppmv; CH_4 = 760 ppbv; N_2O = 270 ppbv; orbital parameters = 1950 yr; solar constant = 1365 W m^{-2}
Modasia-mt	Based on Modasia-ntp, the main TP was added in the modern location
Modasia-tp	Based on Modasia-ntp, the whole TP was added into the modern location
Mod-ntp	Modern geography and SSTs; topography in Eurasia and Africa higher than 300 m set to 300 m; modern land cover; CO_2 = 280 ppmv; CH_4 = 760 ppbv; N_2O = 270 ppbv; orbital parameters = 1950 yr; solar constant = 1365 W m^{-2}
Mod-mt	Based on Mod-ntp, the main TP was added in the modern location
Mod-tp	Based on Mod-ntp, the whole TP was added in the modern location
30ma-ntp	~30 Ma geography and SSTs; topography in Eurasia and Africa higher than 300 m set to 300 m; idealized vegetation (broadleaf evergreen temperate shrubs); no ice sheet; CO_2 = 980 ppmv; CH_4 = 760 ppbv; N_2O = 270 ppbv; orbital parameters = 1950 yr; solar constant = 1365 W m^{-2}
30ma-mt	Based on 30ma-ntp, the main TP was added in the modern location
30ma-tp	Based on 30ma-ntp, the whole TP was added in the modern location

accompanied boundary conditions – including the land-sea distribution, the topography, atmospheric CO_2 concentration and the associated sea surface temperatures (SSTs) – would differ from the modern boundary conditions. Previous modelling studies were mainly based on modern boundary conditions and only a few studies had accounted for the uplift of the TP in specific geological periods (e.g., Jiang et al., 2008; Huber and Goldner, 2012; Zhang, Z.S. et al., 2012; Liu et al., 2017). It remains unclear how changed boundary conditions influence the effects of the uplifts of the main and marginal TP on climate.

We used numerical modelling to compare the effects of the uplifts of the main and marginal TP on climate and to investigate the impact of changed boundary conditions on these climate effects. The simulations investigating the impact of changed boundary conditions were conducted in two steps. First, we investigated the impact of the topography in Europe and Africa because many previous studies included this topography when modelling the uplift of the TP on climate (e.g., Liu and Yin, 2002; Zhang, R. et al., 2012). Second, we further investigated the impact of changes in the land-sea distribution, atmospheric CO_2 concentration and associated SSTs by changing the boundary conditions from modern to ~30 Ma (Scotese, 2001; Zhang et al., 2014). We chose ~30 Ma because this period had very different boundary conditions from present day. Because of uncertainties in the extent and height of the TP in different geological periods, our aim was not to accurately simulate the effects of the uplifts of the main and marginal TP on climate by considering all possibilities from the impact of changed boundary conditions. Instead, we aimed to emphasize the differences of the effects of the uplifts of the main and marginal TP on climate and the impact of changed boundary conditions on these climate effects.

The remainder of the paper is organized as follows. Section 2 describes the model and experimental design. Section 3 presents the model results, with a focus on the response of the Asian climate to the uplift of the TP, including the annual surface air temperature (SAT), annual precipitation, summer and winter low-level (850 hPa) winds, wind seasonality and monsoon domain. Section 4 provides the discussion and Section 5 presents the conclusions.

2. Model and experimental design

2.1. Model

Version 4 of the Community Atmosphere Model (CAM4) from the National Center for Atmospheric Research was used with a horizontal resolution of ~1° (~0.9° latitude × 1.25° longitude) and 26 vertical layers. CAM4 used a finite volume dynamical core (Lin, 2004) and the deep convection process was treated with the parameterization scheme developed by Zhang and Mcfarlane (1995) and modified by Richter and Rasch (2008) and Raymond and Blyth (1986, 1992). A freeze-dry modification was also added to the low cloud parameterization (Vavrus and Waliser, 2007). Version 4 of the Community Land Model (CLM4) (Lawrence et al., 2011), which used the same horizontal resolution as CAM4, was included in the simulations. In CLM4, multiple types of land surface and plant function could be contained within one grid. We used the fixed vegetation rather than the dynamic vegetation model. The performance of CAM4 was evaluated by Zhang et al. (2017) and demonstrated good reproduction of the broad features of the modern annual SAT, annual precipitation, summer precipitation and low-level wind field, winter sea-level pressure (SLP) and low-level wind field in Asia.

2.2. Experimental design

Three groups, each with three experiments, were conducted in total (Table 1). The three experiments were (1) no TP, (2) main TP only and (3) the whole TP. Because of the uncertainties in the extent and height of the TP in geological time periods, the height and extent of the main and marginal TP were kept unchanged in our experiments (Fig. 1A–B). The main TP includes the central and southern TP and Himalaya, and the marginal TP includes the western TP (including the Hindu Kush Mountains), the eastern TP (including the Yungui Plateau), the northern TP (including Altun and Qilian Mountains) and the Tianshan Mountains. In the first group of experiments, the first experiment (Modasia-ntp) was based on the modern geography and SSTs (Fig. 1D–E), with the topography east of 65°E in Asia set to a maximum height of 300 m. Based on experiment Modasia-ntp, we then added the main and whole TP in experiments Modasia-mt and Modasia-tp, respectively (Fig. 1A–B). In the second group, the first experiment was also based on the modern geography and SSTs, but lowered the modern topography in Eurasia and Africa to a maximum height of 300 m (Mod-ntp). Based on experiment Mod-ntp, we then added the main and whole TP (Mod-mt and Mod-tp). The model results in these two groups can be used to investigate the effects of the uplifts of the main and marginal TP on climate and the impact of the topography in Europe and Africa on these climate effects.

The three experiments in the third group were conducted under the boundary conditions at ~30 Ma and an atmospheric CO_2 concentration of 980 ppmv (Table 1). The ~30 Ma palaeogeography (Fig. 1C) and SSTs (Fig. 1F–G) were derived from a previous study (Zhang et al., 2014). The ~30 Ma paleogeography differed significantly from that in present day. For example, at ~30 Ma, the Paratethys Sea and Western Tethys Sea were bigger, and the Indian Subcontinent and Australian mainland located further south, accompany with a bigger subcontinent around Indochina (Fig. 1C). The simulated ~30 Ma summer and annual mean SSTs were higher than the modern SSTs in the Indian Ocean and West Pacific (Fig. 1D–G). Idealized vegetation with only broadleaf evergreen temperate shrubs on land was set in these ~30 Ma experiments due to a lack of vegetation data for this time period. As in experiment Mod-ntp, experiment 30ma-ntp lowered the topography in Eurasia and Africa to a maximum height of 300 m. Based on experiment 30ma-ntp, we then added the main and whole TP (30ma-mt and 30ma-tp). A comparison of the model results in the last two groups shows the

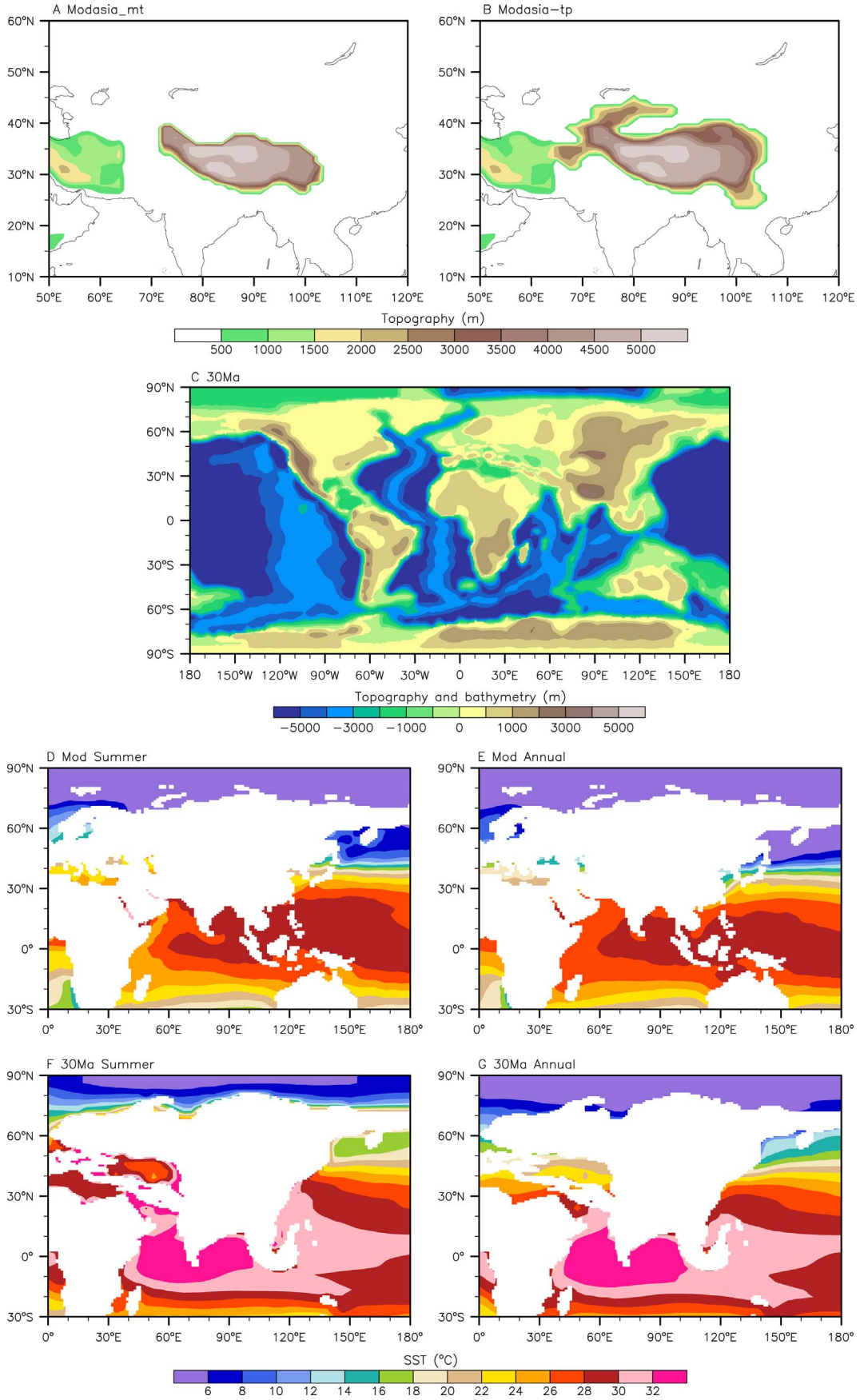
A Modasia_mt
B Modasia−tp
Topography (m)
500 1000 1500 2000 2500 3000 3500 4000 4500 5000
C 30Ma
Topography and bathymetry (m)
−5000 −3000 −1000 0 1000 3000 5000
D Mod Summer
E Mod Annual
F 30Ma Summer
G 30Ma Annual
SST (°C)
6 8 10 12 14 16 18 20 22 24 26 28 30 32

Fig. 1. Topography (m) in experiments (A) Modasia-mt and (B) Modasia-tp, the palaeogeography (m) used in the ~30 Ma experiment (C), and summer and annual SSTs (°C) used in the (D, E) modern and (F, G) ~30 Ma experiments.

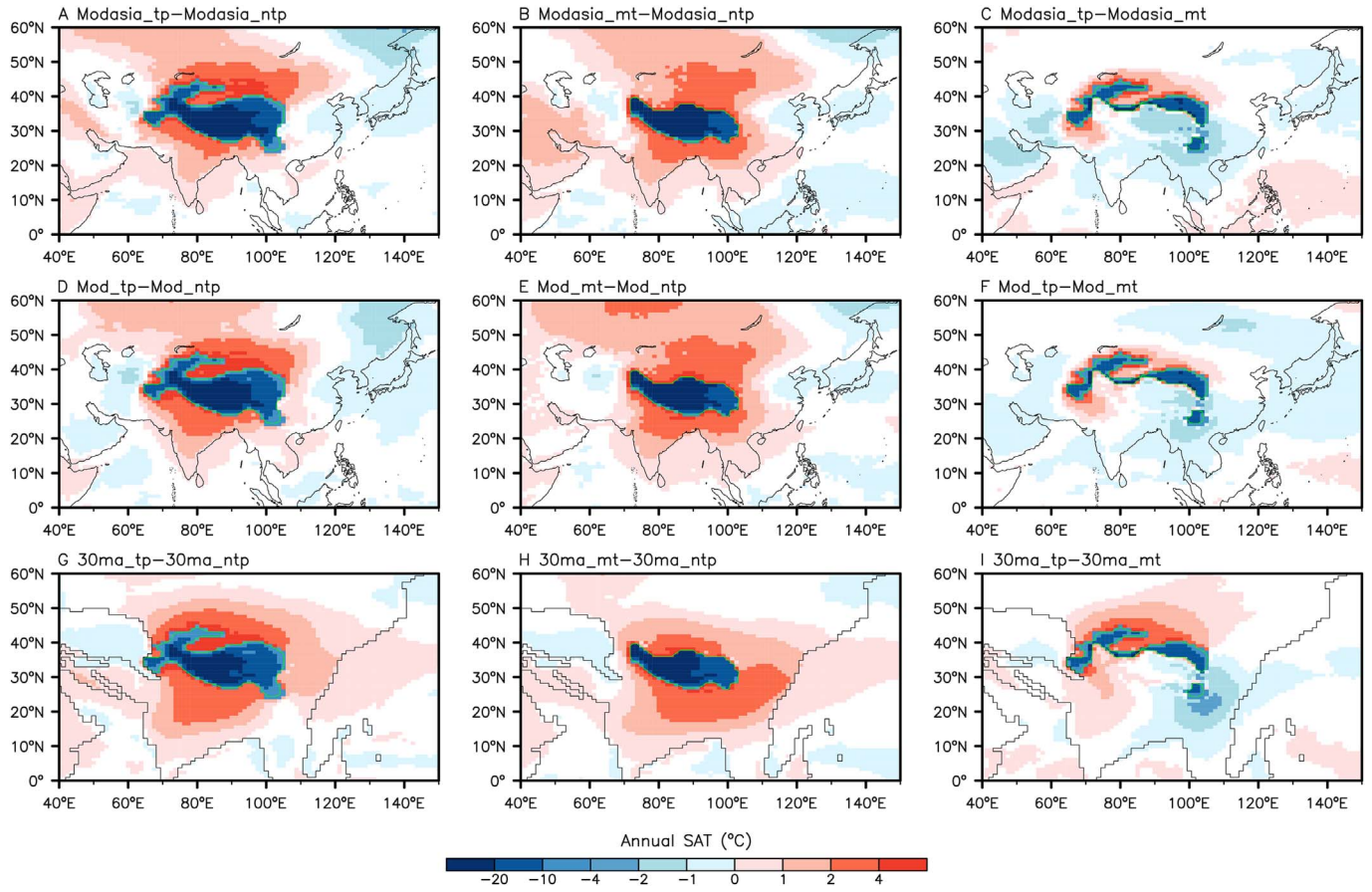

Fig. 2. Differences in the annual SAT (°C) due to uplift of the TP. Only differences that are statistically significant at the 95% confidence level (Student's *t*-test) are illustrated. Topography or topographic changes equal to 1500 m are highlighted (with contours), similar to the following plots.

impact of changes in the land-sea distribution, atmospheric CO_2 concentration and associated SSTs on climate effects of the uplifts of the whole, main and marginal TP.

To focus on the effects of the uplifts of the main and whole TP on climate, we changed only the topography (Fig. 1A–B) and retained the other boundary conditions unchanged in the three experiments within each group (Table 1). Some of the other boundary conditions, including the orbital parameters (year 1950), the solar constant (1365 W m^{-2}) and the concentrations of atmospheric greenhouse gases (set to pre-industrial values) other than atmospheric CO_2 were unchanged in all nine experiments.

Each experiment was run for 25 model years. As the first five model years allowed the simulation to reach a quasi-equilibrium state, the climatological mean derived from the last 20 model years was used in the analysis. We focused on the analysis of the climatic response to the uplifts in annual mean, boreal summer (June, July and August) and boreal winter (December, January and February).

3. Model results

3.1. Annual SAT

The uplift of the whole TP decreased the annual SAT over the uplifted regions due to the effects of the temperature lapse rate, but significantly increased the annual SAT in adjacent areas. However, the change in SAT in the areas adjacent to the TP differed under the three boundary conditions (Fig. 2A, D and G). For example, the decreased SAT on the west side of the TP was different under the two modern boundary conditions (Fig. 2A vs. D). This was because the cold air flow from inland Asia was stronger under the boundary condition without high topography west of 65°E in Eurasia and Africa (Fig. 2D vs. A). By comparison, under the ~30 Ma boundary conditions, the SAT increased more over the Indian peninsula and on the east side of the TP (Fig. 2G).

Significantly, the changed SAT caused by the uplift of the main TP contributed more to the change caused by the uplift of the whole TP (Fig. 2). These effects of the uplift of the main TP on climate also differed under the three boundary conditions; in particular, the amplitude and range of the increased SAT around the TP differed markedly between the modern and ~30 Ma boundary conditions (Fig. 2). Moreover, the effects of the uplift of the marginal TP on climate were also different between the modern and ~30 Ma boundary conditions. Under the ~30 Ma boundary conditions, the uplift of the marginal TP significantly increased the SAT on the north side of the TP and the south side of the western TP (Fig. 2I), whereas the range of the increased SAT in these regions was smaller under the modern boundary conditions (Fig. 2C and F).

3.2. Annual precipitation

The change in annual precipitation due to the uplift of the whole TP also differed under the three boundary conditions. Under the two modern boundary conditions, the uplift of the whole TP increased precipitation over South and East Asia, but decreased precipitation on the north and west sides of the TP (Fig. 3A and D). The model results generally agreed with previously reported results (e.g., Kutzbach et al., 1989; Jiang et al., 2008). However, the effects of the uplifts on climate differed under the two modern boundary conditions; in particular, the amplitude of increased precipitation in South Asia differed significantly (Fig. 3A vs. D). Under the ~30 Ma boundary conditions, increased precipitation occurred in some local areas on the west coast of the

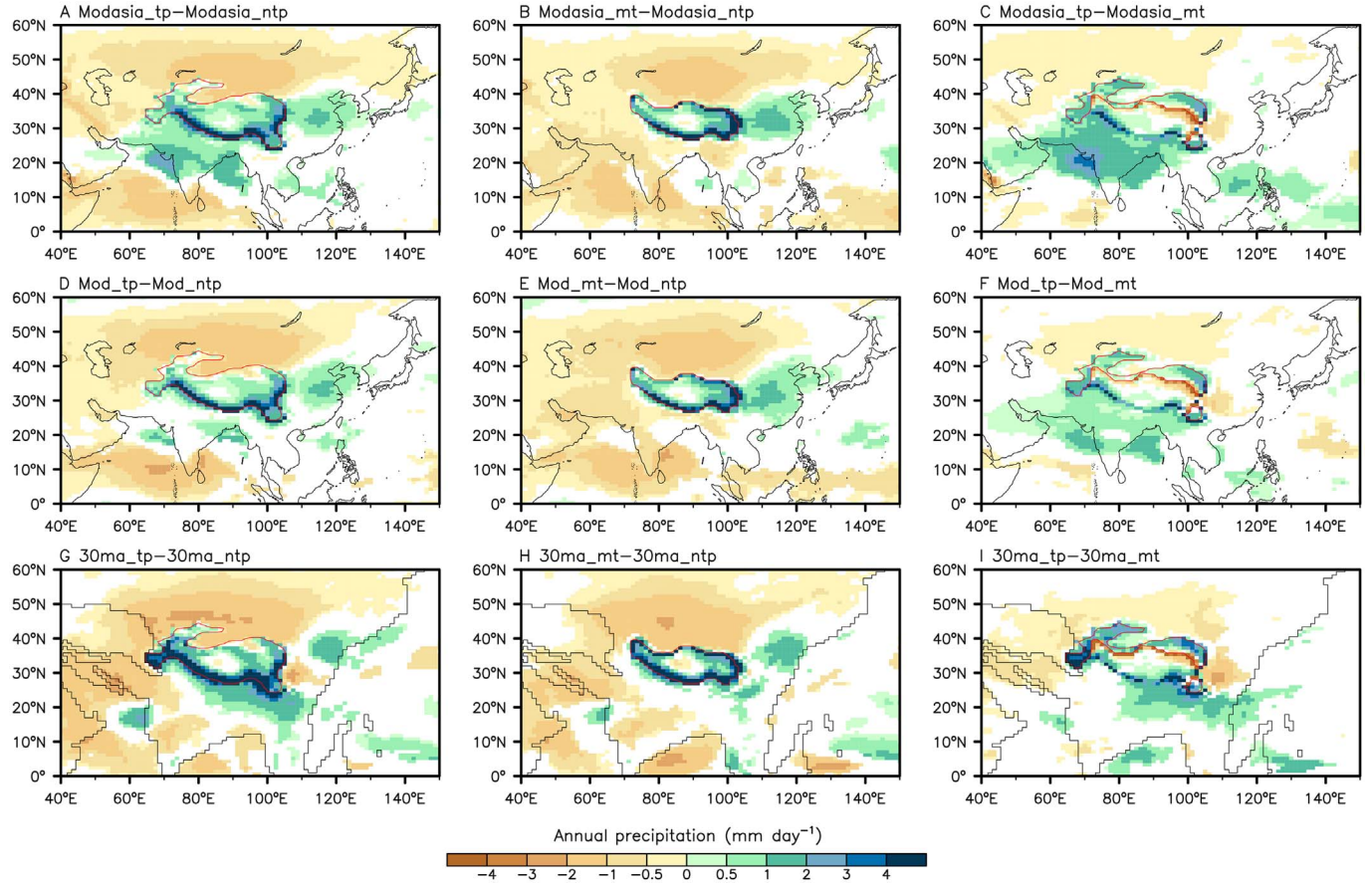

Fig. 3. Differences in annual precipitation (mm day^{-1}) due to the uplift of the TP. Only differences that are statistically significant at the 95% confidence level (Student's *t*-test) are illustrated.

Indian peninsula, on the southeast side of the TP and in northern East Asia and there was also decreased precipitation over the Indian peninsula and on the east side of the TP (Fig. 3G).

The effects of the uplifts of the main and marginal TP on the annual precipitation were also different. Under all three boundary conditions, the uplift of the main TP contributed more to the increased precipitation in East Asia and decreased precipitation on the north side of the TP (Fig. 3B, E and H). By contrast, the uplift of the marginal TP led to increased precipitation in South Asia and slightly decreased precipitation on the north side of the plateau (Fig. 3C, F and I). The increased precipitation in South Asia was significantly different under the three boundary conditions (Fig. 3C, F and I), which mainly contributed to the different effects of the uplift of the whole TP in this area.

3.3. Summer low-level winds

The uplift of the whole TP had different effects on summer precipitation and low-level winds under the three boundary conditions. After the uplift of the whole TP under the modern boundary conditions with high topography west of 65°E in Eurasia and Africa, southwesterlies strengthened in the Arabian Sea and Indian peninsula, whereas southerlies and southeasterlies markedly strengthened in East China (Fig. 4A). Precipitation increased more in the northeastern Arabian Sea, Indian peninsula, the southern/eastern edge of the TP and northern East Asia (Fig. 4A). These results generally agree with the results of previous studies (e.g., Jiang et al., 2008; Tang et al., 2013). If the whole TP rose in the absence of high topography west of 65°E in Eurasia and Africa, anomalous dry northeasterlies appeared on the west side of the TP and the increased precipitation was less in South Asia (Fig. 4D vs. A). Meanwhile, the increase in precipitation was greater in northern East Asia, consistent with stronger southerlies and southwesterlies in East Asia (Fig. 4D vs. A). By comparison, the uplift of the whole TP under the ~30 Ma boundary conditions led to markedly cyclonic circulation anomalies around the uplifted region. Precipitation increased on the west coast of the Indian peninsula and on the south side of the TP in South Asia (Fig. 4G).

The uplifts of the main and marginal TP also had different effects on summer precipitation and low-level winds. Under the modern boundary conditions in the presence of the high topography west of 65°E in Eurasia and Africa, the uplift of the main TP led to cyclonic circulation anomalies around the uplifted region. Precipitation greatly increased in the uplifted region and in northern East Asia, but decreased in other adjacent areas of the TP (Fig. 4B). If the main TP rose without high topography west of 65°E in Eurasia and Africa, the pattern of changed precipitation and winds was similar to that in the previous condition, but with stronger anomalous northeasterlies on the west side of the plateau and stronger anomalous southerlies in northern East Asia relative to the previous condition (Fig. 4E vs. B). The cyclonic circulation anomalies around the TP still existed under the ~30 Ma boundary conditions, but there was no increase in precipitation in northern East Asia (Fig. 4H). Under the modern boundary conditions with high topography west of 65°E in Eurasia and Africa, the further uplift of the marginal TP markedly strengthened the southwesterlies in the Arabian Sea and increased precipitation in the northeastern Arabian Sea and Indian peninsula (Fig. 4C). This increased precipitation was weaker due to the anomalous dry northeasterlies on the west side of the TP under modern boundary conditions without high topography west of 65°E in Eurasia and Africa (Fig. 4F vs. C). This increased precipitation was further limited under the ~30 Ma boundary conditions and was only seen on the west coast of the Indian peninsula and on the northeastern

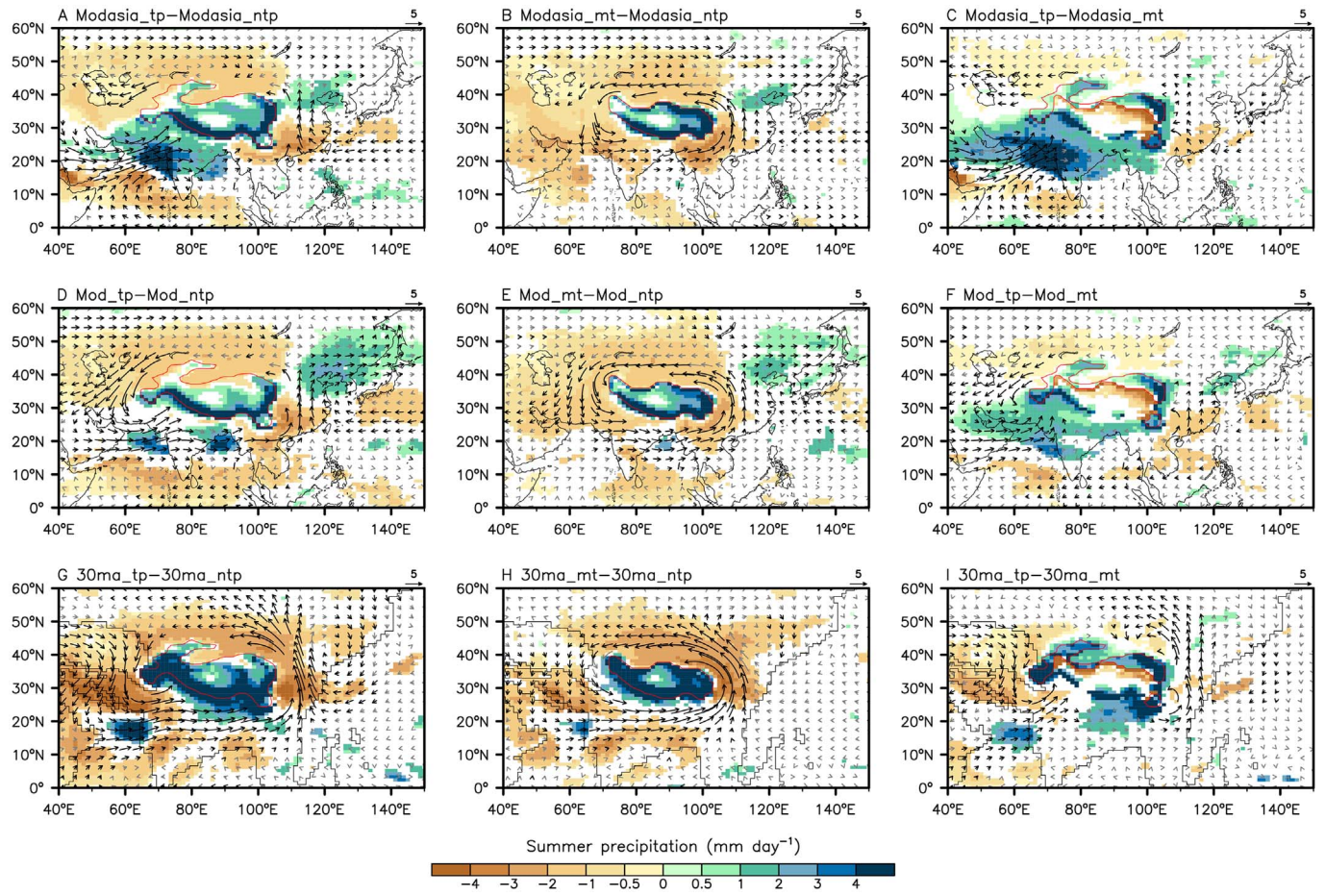

Fig. 4. Differences in summer precipitation (shaded, mm day^{-1}) and 850 hPa winds (vectors, m s^{-1}) due to uplift of the TP. Only differences that are statistically significant at the 95% confidence level (Student's *t*-test) are illustrated for precipitation and shown as black vectors for winds.

part of the Indian peninsula in South Asia (Fig. 4I).

The change in precipitation was closely related to the change in vertical movement (Fig. 5) and the transport of water vapour (not shown). The increased precipitation in the northeastern Arabian Sea, Indian peninsula, and northern East Asia as a result of the uplift of the whole TP under the two modern boundary conditions was closely related to the anomalous upward movement (Fig. 5A and D) and convergence of water vapour (not shown). This anomalous upward movement (Fig. 5G) and convergence of water vapour (not shown) only appeared on the west coast of the Indian peninsula and on the south side of the TP in South Asia under the ~30 Ma boundary conditions, consistent with the increased precipitation in these regions (Fig. 4G). Because the changes in vertical movement (Fig. 5) and transport of water vapour (not shown) due to the uplifts of the main and marginal TP were markedly different under the three boundary conditions, the resultant change in precipitation also differed accordingly (Fig. 4).

3.4. Winter low-level winds

Similar to the change in summer low-level winds, the change in the winter SLP and low-level winds also differed markedly as a result of the uplift of the whole TP under the three boundary conditions. After the uplift of the whole TP under the modern boundary conditions with high topography west of 65°E in Eurasia and Africa, the SLP increased more on the north side of the plateau, accompanied by anomalous anticyclonic circulation (Fig. 6A). When the whole TP rose under the modern boundary conditions without high topography west of 65°E in Eurasia and Africa, the increase in SLP on the north side of the plateau became weaker (Fig. 6D). Stronger anomalous westerlies occurred on the south side of the TP due to a greater decreased SLP on the south side of the TP compared with the previous condition (Fig. 6D vs. A). By contrast, under the ~30 Ma boundary conditions, the increased SLP centre on the north side of the plateau located further north and the decreased SLP on the south side of the TP became stronger. Stronger anomalous easterlies and westerlies were seen on the north and south sides of the plateau, respectively (Fig. 6G).

Under the three boundary conditions, the effects of the uplift of the main TP contributed more to the effects of the uplift of the whole TP, with strengthened SLP on the north side of the TP and a decreased SLP around the TP (Fig. 6B, E and H). In a similar manner to the effects of the uplift of the whole TP, the changed boundary conditions from the modern to ~30 Ma also affected the effects of the uplift of the main TP. For example, under the ~30 Ma boundary conditions, the uplift of the main TP markedly strengthened the anomalous cyclonic circulation around the TP and there were stronger anomalous easterlies and westerlies on the north and south sides of the TP, respectively (Fig. 6H). By contrast, the uplift of the marginal TP exerted weaker effects, which further changed under different boundary conditions. For example, under the ~30 Ma boundary conditions, anomalous northerlies occurred on the east side of the TP, consistent with more strengthened SLP in the adjacent regions (Fig. 6I).

3.5. Wind seasonality and monsoon domain

The uplift of the whole TP had important, but different, effects on the seasonality of winds under the three boundary conditions. Under the two modern conditions without the TP, the regions with the high wind seasonality (angles between summer and winter low-level

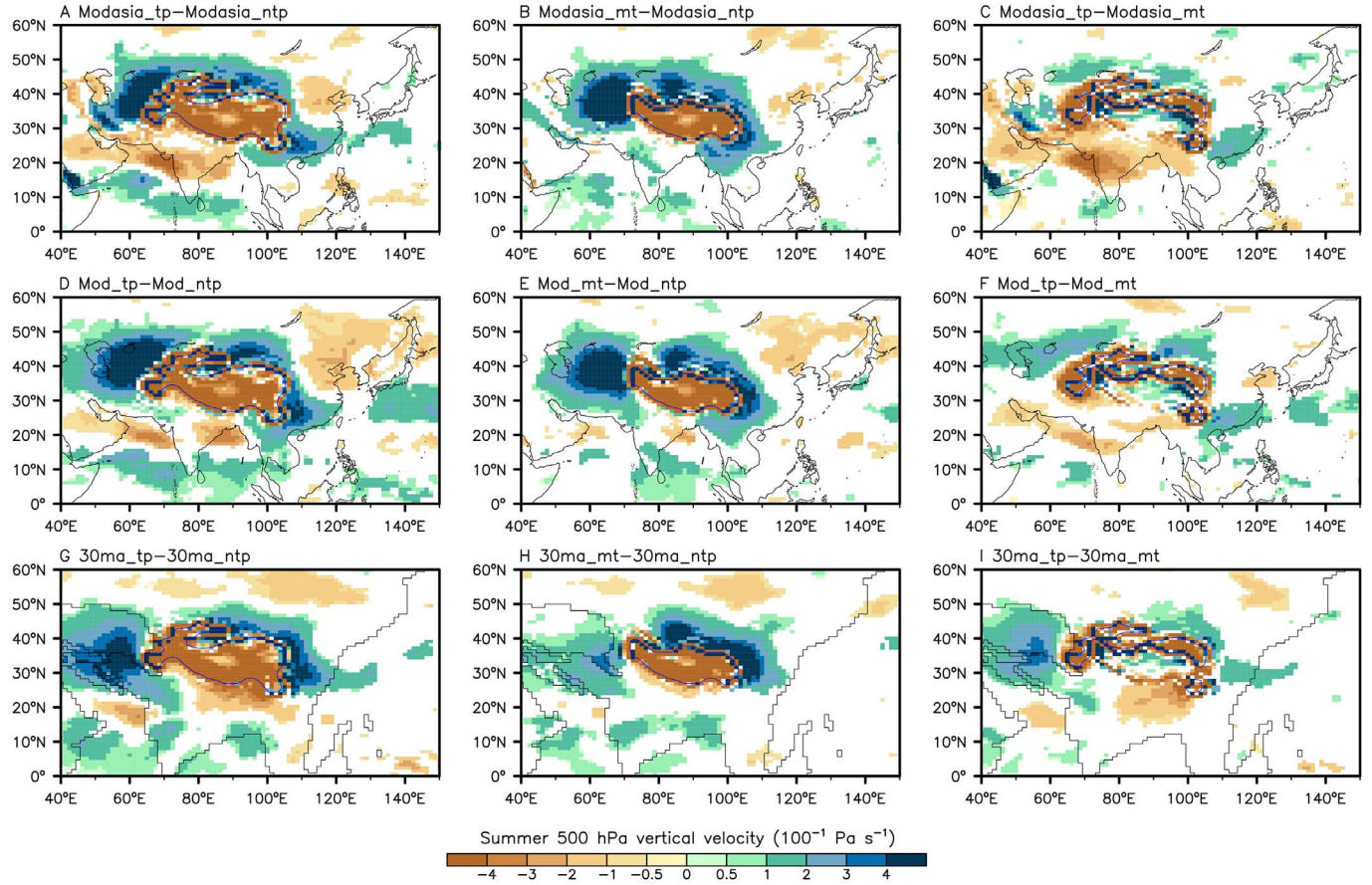

Fig. 5. Differences in summer 500 hPa vertical velocity (100^{-1} Pa s^{-1}) due to uplift of the TP. Upward motion is negative and downward motion is positive. Only differences that are statistically significant at the 95% confidence level (Student's *t*-test) are illustrated.

winds > 100°) were similar and mainly located in regions south of ~30°N (Fig. 7A and D). By contrast, under the ~30 Ma boundary conditions without the TP, the regions with the high wind seasonality were mainly located in regions west of ~100°E (Fig. 7G). After the uplifts of the main and whole TP, the regions with the high wind seasonality changed moderately. In detail, under the two modern boundary conditions, the uplift of the main TP enhanced the high wind seasonality on the north side of the TP, but weakened the high wind seasonality on the east side of the TP (Fig. 7B and E), whereas the uplift of the marginal TP slightly enhanced the high wind seasonality on the east side of the plateau (Fig. 7C and F). By contrast, under the ~30 Ma boundary conditions, the uplift of the main TP enhanced the high wind seasonality on the northwest side of the TP, but weakened the high wind seasonality on the south side of the TP. After the uplift of the marginal TP, the high wind seasonality was enhanced on the north side of the TP and on the south side of the eastern TP. Meanwhile, there were almost no regions with the high wind seasonality in East Asia east of ~105°E (Fig. 7H and I).

The uplift of the whole TP and its sub-regions also affected the domain of the Asian monsoon. If the monsoon domain was defined in terms of the seasonality of precipitation (Wang et al., 2012), when there was no TP, the Asian monsoon domain was similar under the two modern boundary conditions, whereas there was an area without monsoon domain in East Asia east of ~105°E under the ~30 Ma boundary conditions (Fig. 8A, D and G). Under the two modern boundary conditions, the monsoon domain decreased in size on the east side of the TP after the uplift of the main TP (Fig. 8B and E), whereas the monsoon domain increased in size in this region after the uplift of the marginal TP (Fig. 8C and F). Under the ~30 Ma boundary conditions, the monsoon domain decreased markedly on the north and northeast sides of the plateau after the uplift of the main TP (Fig. 8H), and there was still no monsoon domain in East Asia east of ~105°E after the further uplift of the marginal TP (Fig. 8I).

4. Discussion

4.1. Effects of the uplifts on climate under different boundary conditions

The changes in the summer and winter winds were related to the changes in thermal structure. Taking the summer temperature change at 800 hPa as an example (Fig. 9), the changed temperature pattern was similar under the two modern boundary conditions, with increased and decreased temperature on the north and south sides of the TP, respectively (Fig. 9A and D). By contrast, under the ~30 Ma boundary conditions, the change in the pattern of summer temperature was markedly different from that under the modern boundary conditions (Fig. 9G), with stronger warming on the north side of the uplifted TP. The changes in temperature were also different between the uplifts of the main and marginal TP under the three boundary conditions, and the change in temperature due to the uplift of the main TP contributed more to the change in temperature by the uplift of the whole TP (Fig. 9). As a result of the different changes in temperature and the further land-sea thermal contrast, the changes in the summer and winter winds were thus different under the three boundary conditions.

The different boundary conditions affected the changes in the thermal structure caused by the uplifted plateau. The TP is a heat source in summer and a cold source in winter (Kutzbach et al., 1989; Liu and Yin, 2002). The TP significantly affects the thermal structure of the atmosphere through its thermal and mechanical effects. Previous studies indicated that the heating effects in summer and the mechanical

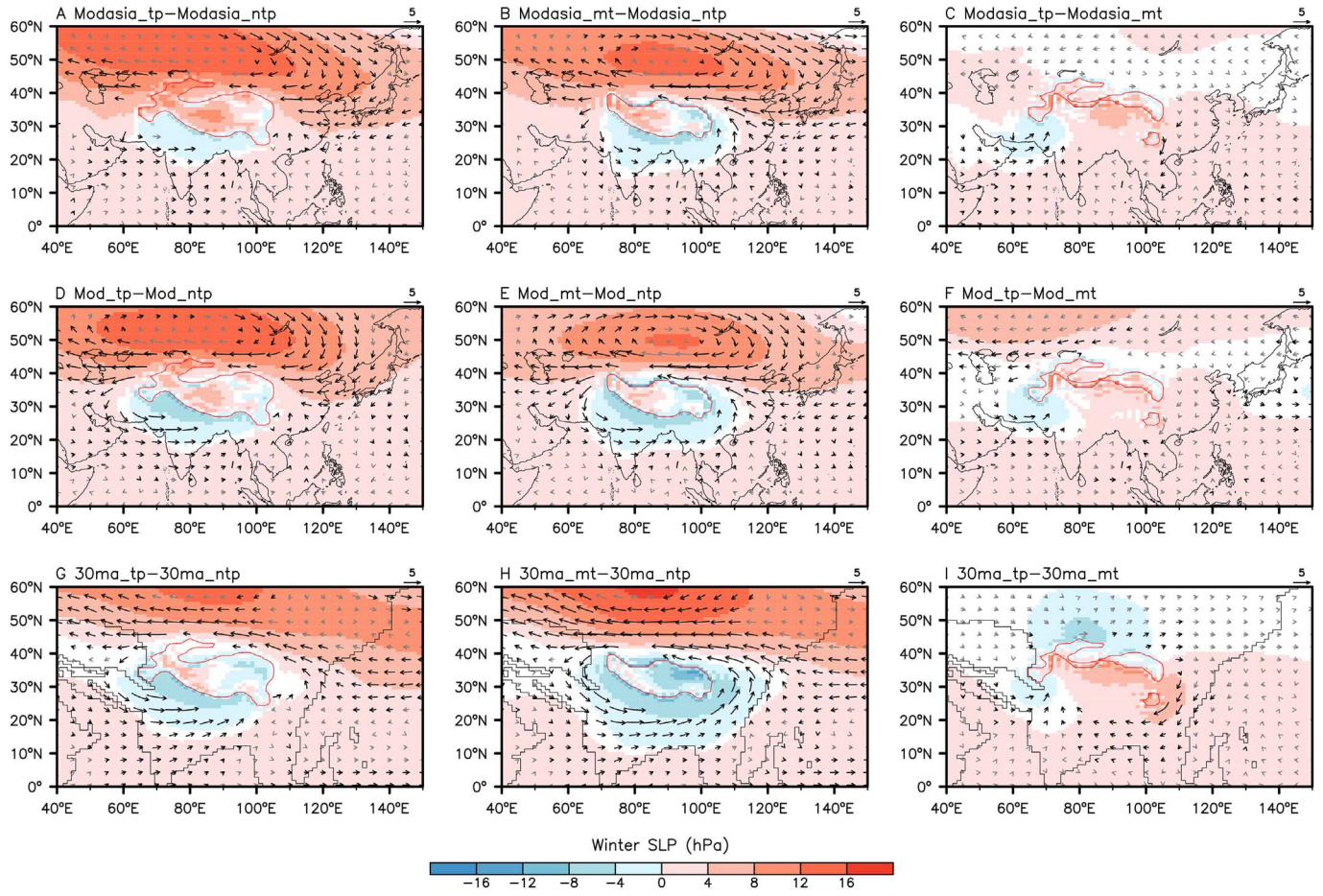

Fig. 6. Differences in winter SLP (shaded, hPa) and 850 hPa winds (vectors, m s^{-1}) due to uplift of the TP. Only differences that are statistically significant at the 95% confidence level (Student's *t*-test) are illustrated for SLP and shown as black vectors for winds.

effects in winter of the northern East Asian mountains were affected by changes in the topographic boundary conditions (Zhang et al., 2017). Our results further indicated that the effects of the uplifts of the TP and its sub-regions on climate were further affected by other boundary conditions, including the changed land-sea distribution, atmospheric CO_2 concentration and associated SSTs. The changes in these boundary conditions would adjust the heating effects of the plateau in summer and the mechanical effects of the plateau in winter and further affected the thermal structure of the atmosphere due to the uplift of the plateau, which, in turn, influenced the change in the summer and winter winds. Thus, we need to fully consider the effects of the boundary conditions when investigating the effects of the uplifts of the TP and its sub-regions on climate.

4.2. Implications for the Asian climate evolution

Our results suggest that the uplift of the marginal TP was also important in the evolution of the Asian climate. The uplift of the main TP was important in many respects – for example, in the large-scale changes in the annual SAT (Fig. 2), the decreased annual precipitation in inland Asia north of the TP and in the increased annual precipitation in East Asia (Fig. 3). In some respects, however, the uplift of the main TP had limited effects. For example, the uplift of the main TP did not increase the annual and summer precipitation in South Asia (Figs. 3 and 4), whereas the uplift of the marginal TP markedly increased both the annual and summer precipitation in South Asia (Figs. 3 and 4). Thus, although the main TP is the major part of the TP in spatial terms, the effect of its uplift is not dominant in the effects of the whole TP on the Asian climate in all aspects.

Because the effects of the uplifts of the main and marginal TP on climate were different, the response of the Asian monsoon climate and the aridity of inland Asia to the uplift of the TP in the Cenozoic would be asynchronous. Within the uncertainties of the uplift history of the TP, if the main TP uplifted earlier than the marginal TP, the first uplift of the main TP would significantly decrease the annual precipitation in inland Asia (Fig. 3) and the later uplift of the marginal TP would markedly increase the annual precipitation in South Asia (Fig. 3), which means that the enhanced inland Asian aridity affected by the uplift of the TP probably occurred earlier than the increased South Asian precipitation affected by the uplift of the TP. The uplifts of both the main and marginal TP decreased the annual precipitation in inland Asia (Fig. 3), which implies that the effect of the uplift of the TP on the aridity of inland Asia probably occurred in several distinct steps.

However, it seems that the uplift of the TP could not change the monsoon climate in South Asia west of ~100°E. Although the uplifts of the main and marginal TP changed the precipitation in South Asia, there was always a monsoon domain with high wind and precipitation seasonality in South Asia west of ~100°E, irrespective of the presence or absence of the TP (Figs. 7 and 8). Thus, the South Asian monsoon climate west of ~100°E formed mainly due to other forcings – such as changes in the land-sea distribution (e.g., Xu et al., 2010) – and the uplift of the TP only modulated the intensity of the monsoon climate in these regions. The East Asian climate, however, was more complex. In particular, without the TP, there was a monsoon climate with high wind and precipitation seasonality in East Asia east of ~105°E under the modern boundary conditions, but there was no monsoon climate in East Asia east of ~105°E under the ~30 Ma boundary conditions (Figs. 7 and 8). Although our model results indicated that the uplifts of the main

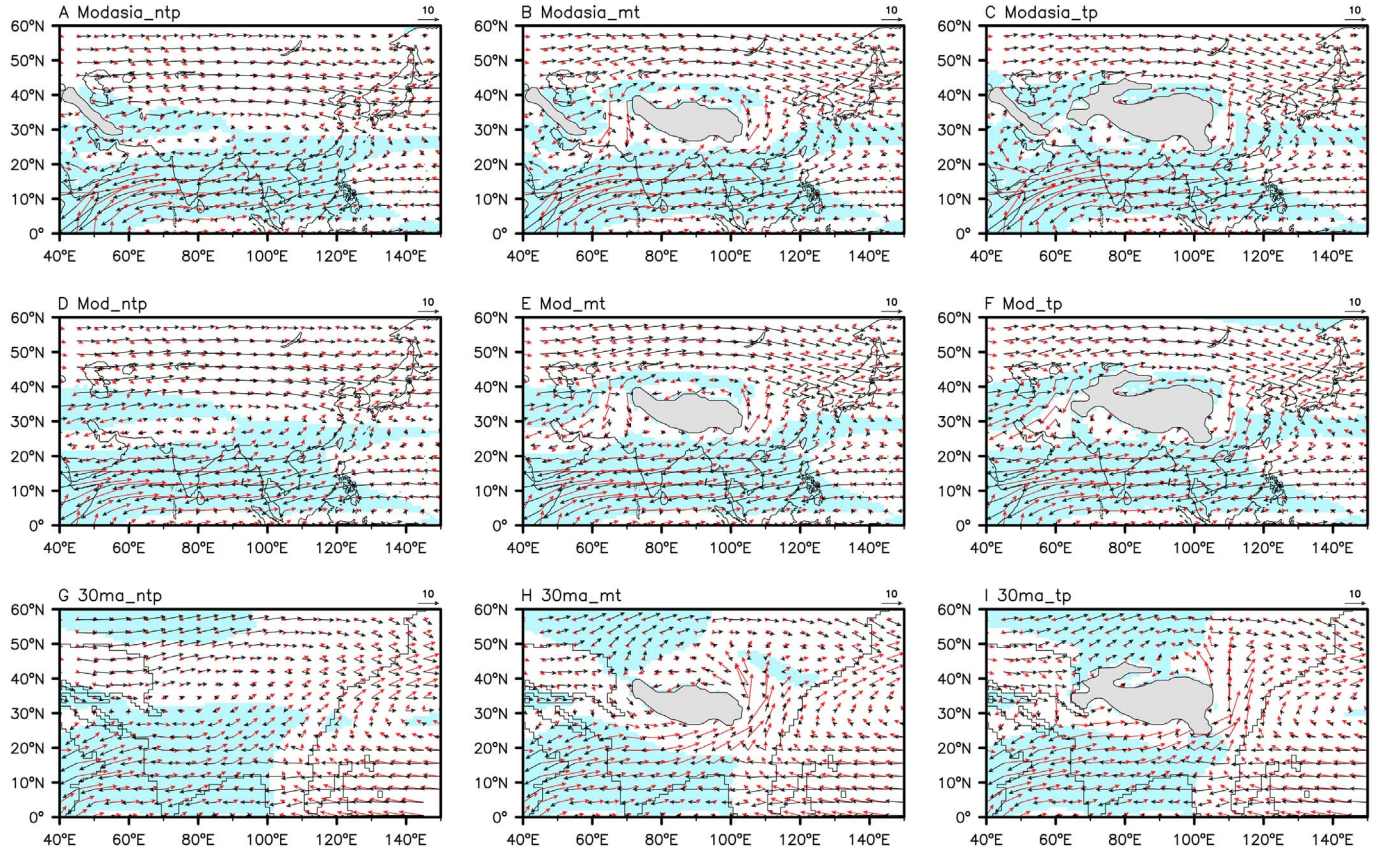

Fig. 7. Comparison of wind seasonality. Red arrows show summer 850 hPa winds and black arrows show winter 850 hPa winds ($m\ s^{-1}$). The areas where the angles between summer and winter winds are > 100° are shown in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

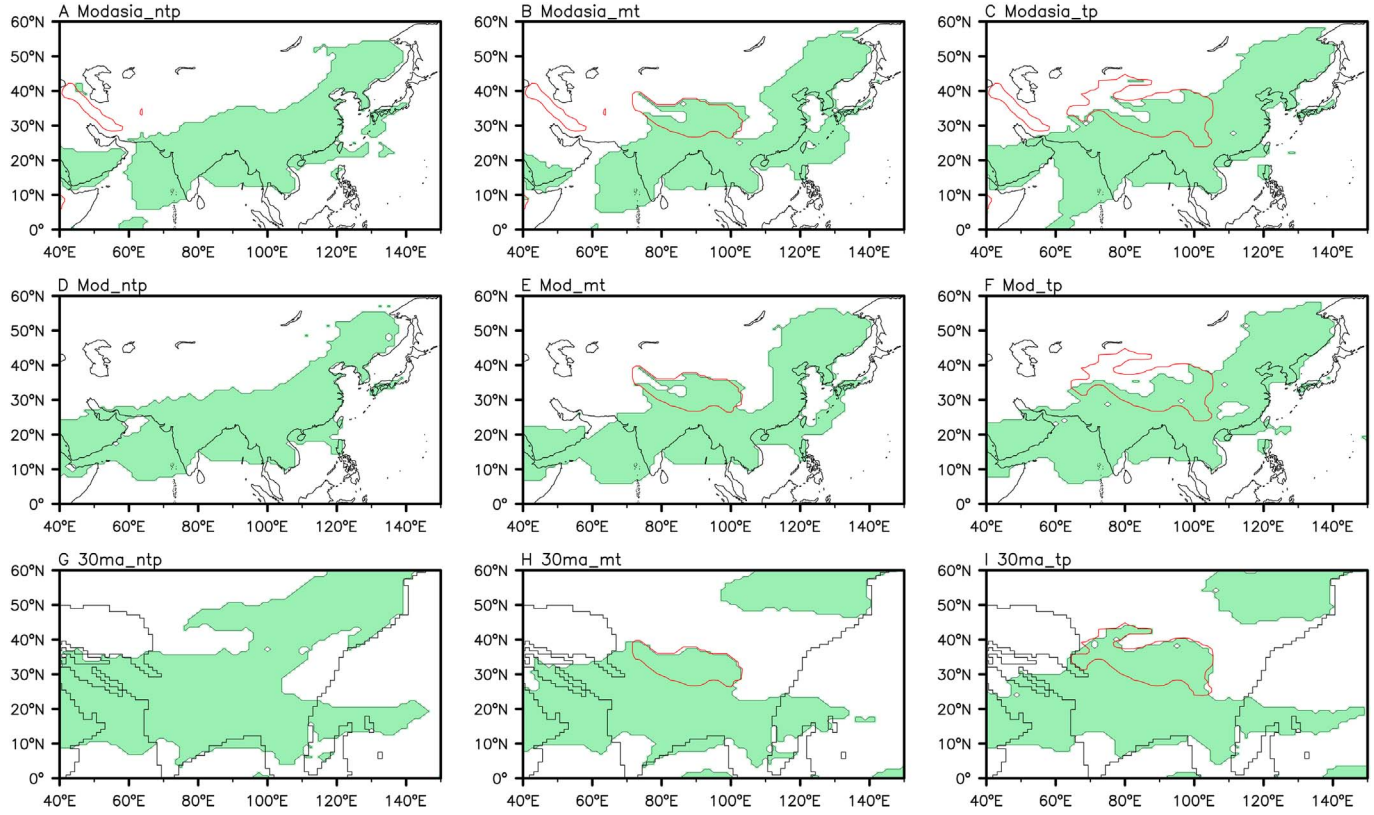

Fig. 8. Distribution of the monsoon domain. The monsoon domain is defined by Wang et al., 2012 with the summer (May to September) precipitation minus the winter (November to March) precipitation > 2.0 mm day^{-1} and the local summer precipitation > 55% of the annual total precipitation.

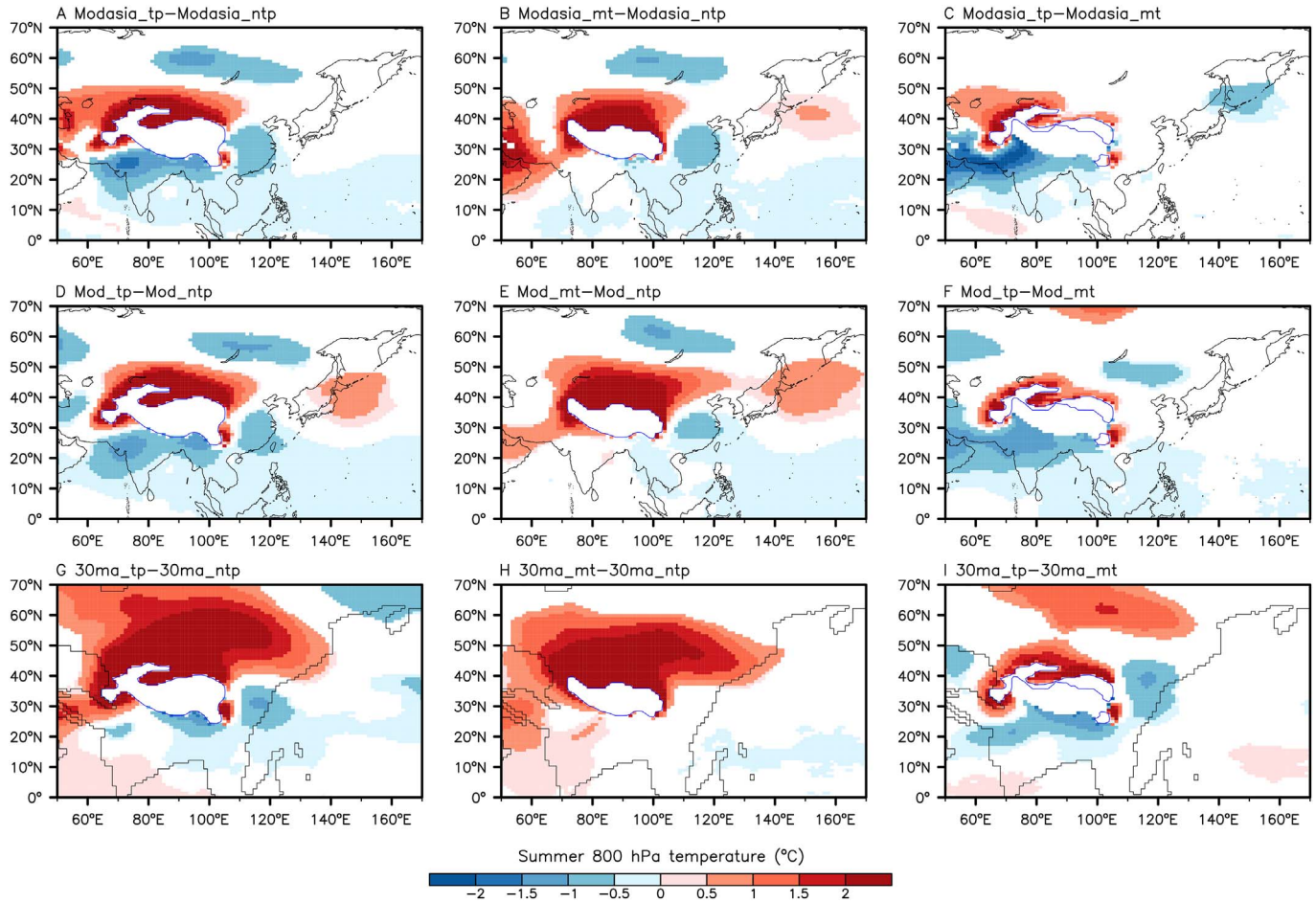

Fig. 9. Differences in summer 800 hPa temperature (°C) due to uplift of the TP. Only differences that are statistically significant at the 95% confidence level (Student's *t*-test) are illustrated.

and marginal TP had an effect on the planetary subtropical aridity pattern at ~30 Ma in East Asia (e.g., Guo et al., 2008), the uplift did not change the monsoon climate in East Asia east of ~105°E under the modern boundary conditions or the non-monsoon climate in East Asia east of ~105°E under the ~30 Ma boundary conditions (Figs. 7 and 8). Thus, the presence or absence of a monsoon climate in East Asia under the modern or ~30 Ma boundary conditions was likely affected significantly by the changes in other boundary conditions, such as the land-sea distribution, the atmospheric CO_2 concentration and the associated SSTs (Ramstein et al., 1997; Bosboom et al., 2014; Lu and Guo, 2014; Carrapa et al., 2015). More experiments are thus needed to investigate the effects of these changed boundary conditions on the East Asian climate in the future.

4.3. Uncertainties

We only considered the uplifts of the main and marginal TP. The actual uplift process would be more complex than what we have considered here (Harris, 2006), and the uplift history across different regions of the marginal TP was also probably asynchronous. There were still debates about the uplift history of the TP and some study indicated that some regions on the NE margin of the TP had already become high enough to affect the climate in the Eocene (e.g., Dupont-Nivet et al., 2008). In addition, we did not consider all the possible impacts of the changed boundary conditions on the climate effects of the uplift of the TP. For example, we did not consider the impact of the topography in the Rocky Mountains of North America. The uplift in the Rocky Mountains of North America might induce shifts in the large-scale planetary waves of the Northern Hemisphere and would then affect the climate effects of the uplifts of the TP and its sub-regions. Moreover, the ~30 Ma boundary conditions were still thought to be ideal for investigating the effects of the uplifts of main and marginal TP on climate. Based on the uplift history of the different regions of the TP, we probably need to investigate the effects of the uplift of the main TP on climate under the Eocene boundary conditions (e.g., Wang et al., 2008; Quade et al., 2011) and the effects of the uplift of the marginal TP under the Miocene and Pliocene boundary conditions (e.g., Sun et al., 2004; Clark et al., 2005; Li et al., 2014). Besides, our use of fixed vegetation overlooked the potential interactions between vegetation and the atmosphere in response to the uplift of the plateau. Although the boundary conditions of vegetation did not play a dominant part in our sensitivity experiments, it is still worth conducting more sensitivity experiments to test its effect on climate. Our model results clearly indicated the different effects of the uplifts of the main and marginal TP on climate and further impact of changed boundary conditions on these climate effects. These main findings were likely robust even if we used more realistic boundary conditions.

5. Conclusions

We conducted several experiments to compare the effects of the uplifts of the main and marginal TP on the Asian climate. The model results indicated that there were differences in the effects of the uplifts on climate between these two regions. Under modern boundary conditions, the uplift of the main TP decreased the annual SAT over the uplifted regions and increased the annual SAT in adjacent areas. The

annual precipitation increased in East Asia and decreased on the north, west and south sides of the TP; in addition, summer low-level cyclonic circulation anomalies were induced around the uplifted region. By contrast, the uplift of the marginal TP increased the annual SAT on the north side of the plateau and on the south side of the western TP, markedly increased the annual precipitation in South Asia, strengthened the summer low-level southwesterlies and increased summer precipitation over the Arabian Sea and Indian peninsula, and strengthened wind seasonality and enlarged the monsoon domain in northern East Asia. Thus, the uplift of the marginal TP was also very important in the evolution of the Asian climate. These effects on climate were also affected by changed boundary conditions, including the topography other than the TP, the land-sea distribution, the atmospheric CO_2 concentration and the associated SSTs.

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